High-Frequency Sound Interaction in Ocean Sediments: Modeling Environmental Controls

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LONG-TERM GOALS

Our long term goal is to develop accurate models for high-frequency acoustic penetration into, propagation within, and scattering from shallow water ocean sediments. This work should specifically improve the Navy's ability to detect buried mines and, in general, improve sonar performance in shallow water. Additional objectives of the NRL program are to understand and model the complex interactions among environmental processes, sediment structure, properties, and behavior. These models allow portability of high-frequency bottom interaction models to sites of naval interest.

OBJECTIVES

Provide statistical characterization of the environmental properties, especially the sediment volume properties, required to determine and model the dominant mechanisms controlling the penetration into and scattering from the seafloor of high-frequency acoustic energy. Determine the effects of biological, geological, biogeochemical, and hydrodynamic processes on the spatial distribution of sediment physical, geotechnical and geoacoustic properties at the experimental site. Develop predictive empirical and physical models of the relationships among those properties.

APPROACH

The "High-Frequency Sound Interaction in Ocean Sediments" DRI addresses high-frequency acoustic penetration into, propagation within, and scattering from the shallow-water seafloor. The primary goal of the proposed study is to understand the mechanisms for high-frequency acoustic energy penetration into sediments at low grazing angles. Sediment volume heterogeneity, in particular, can be a mechanism for this anomalous penetration by scattering the evanescent wave energy that propagates along the seafloor interface into the sediment (Maguer et al., 2000). In order to understand the propagation of high-frequency acoustic energy in sediments and thereby evaluate the predictions of sound penetration into sediments based on this mechanism, the spatial variability of sediment physical and geoacoustic properties must be characterized.

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14. ABSTRACT
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If the high-frequency acoustic bottom interaction models are to be utilized outside specific experimental conditions, the effects of environmental processes (biological, hydrodynamic, geological, and biogeochemical) on the spatial and temporal distribution of properties that control propagation, scattering and penetration phenomena must be understood (Richardson and Briggs, 1996). NRL, working with other DRI investigators, quantified and are modeling these relationships. Using data and samples collected in the field experiment (SAX99), we concentrated our investigation on fluctuations in properties of sediment density, sound speed, and porometry. Porometric properties of porosity, permeability, and tortuosity were investigated by Computed Tomography images, such that actual pore space was measured. Also, scientists from NRL and APL-UW collaborated on statistical characterization of volume heterogeneity for use as input parameters for acoustic scattering models.

WORK COMPLETED

With most of the results from the sediment acoustic experiment (SAX99) conducted in October-November 1999 (FY00) near Destin, Florida already published in the July 2002 special issue of IEEE Ocean Engineering (Eric Thorsos and Mike Richardson, guest editors), efforts in FY03 were concentrated on interpretation and modeling. A simulation experiment using Monte Carlo realizations was performed based on real variations in sound speed and bulk density data from SAX99 sand sediment in order to examine the nature of variability in these two measured parameters. In addition, the cross-correlation between sediment bulk density and sound speed fluctuations was estimated in the same SAX99 cores. Also, sediment porometry was investigated with high-resolution Computed Tomography scanners. A 3D, high-resolution Computed Tomography (CT) image of a medium sand comprised of near-spherical ooids was collected from which separate low- and high-resolution 2D images were realized. From these four images pore geometry and topology were quantified and permeability was predicted using an effective medium theory (EMT) technique. Sediment pore geometry was quantified and mapped in order to produce geometrically realistic pore-scale networks, which determine hydraulic properties of sand and control processes such as drainage, imbibition, and multi-phase flow.

Planning for the follow-up field experiment to SAX99, SAX04, scheduled for September through November 2004, began and the initiation of the agenda was presented at the SAX04 Workshop in Nashville, Tennessee on 27 April 2003. Integral to NRL's contributions to the environmental measurement agenda are:

- Characterizing high-resolution (1 mm) seafloor roughness over a range of scale sufficient for determination of model input parameters for 40kHz as well as 300 kHz with digital stereo photogrammetry
- Measuring seafloor roughness on diver-manipulated (point scatterers and sinusoidal features) interfaces
- Measuring the temporal changes on seafloor roughness due to biological and physical processes and comparing roughness changes with changes in high-frequency acoustic scattering
- Conducting measurements for grain bulk modulus on field and laboratory samples
- Performing and evaluating new in-situ resin impregnation for CT image analysis of pore size, pore throat length, and pore connectivity
- Developing and employing 3D network modeling techniques to provide values porosity, permeability, and tortuosity factor from 3D CT images
- Characterizing sediment bulk density fluctuations at high resolution from CT scans for estimating density power spectra

RESULTS

Variability of sediment bulk density

Sediment bulk density was measured in the medium sand at the SAX99 site with 18 cores and density variations were measured using convention gravimetric laboratory techniques. The sediment density power spectrum was estimated from the fluctuations. The average exponent of the vertical one-dimensional power-law spectra was 2.17 and the average correlation length of the density fluctuations, based on a first-order autoregressive technique, was 3.51 cm. By inverting the spectrum and correlation length data, a simulation of (vertical) density variability was generated. A Fourier-based Monte-Carlo method was used to generate a "virtual" core in three dimensions (Fig.1). A number of realizations were generated by assigning a random Gaussian phase to the simulation and each realization was virtually "sectioned" at the same intervals as the original data. Each virtual section of each virtual core was averaged to obtain the virtual "bulk density" value for that section and compared with original laboratory measurements of cores via correlation length estimation. Because the simulated data diverged from the actual data by having larger estimated correlation lengths, we concluded that smoothing of bulk density occurs when cores are sampled at 2-cm intervals and that this smoothing is responsible for hiding significant variation in bulk density. Thus, high-resolution measurement of sediment bulk density (such as from CT imagery) is necessary for accurate characterization of sediments for modeling high-frequency acoustic scattering from the sea floor.

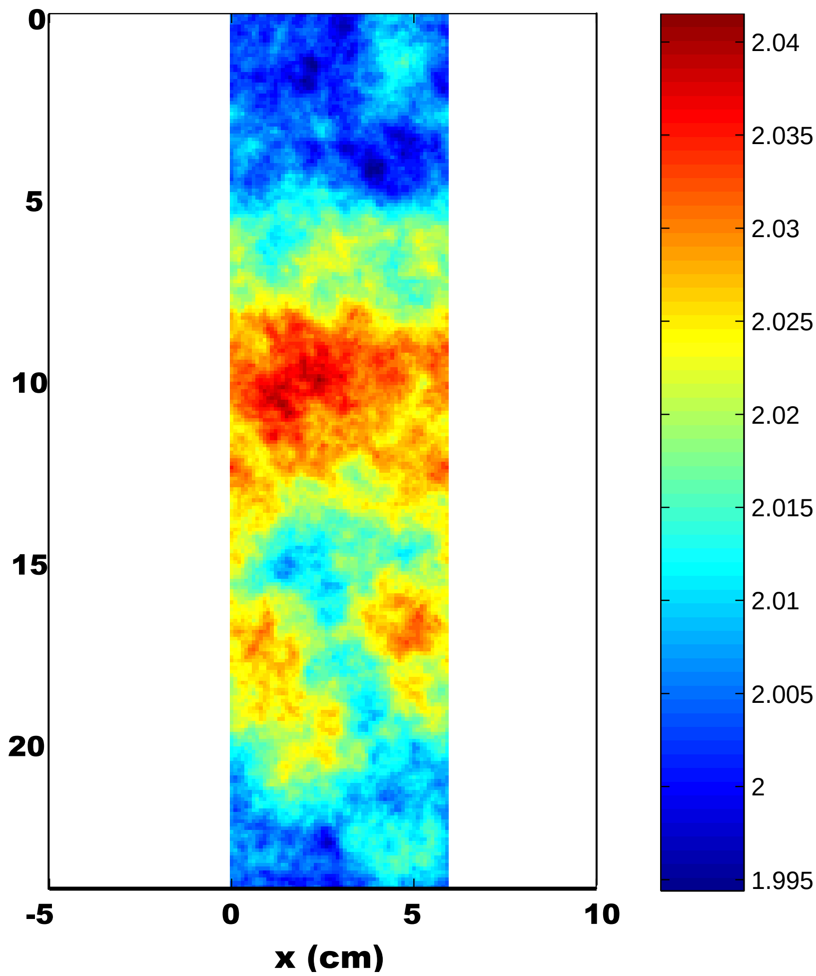

Figure 1. Vertical planar "slice" through one realization of a 3D virtual core, with the variations of sediment bulk density in g/cm^3 indicated by the color scale to the right. Voxel size is 1 mm on a side.

Porometry determinations from ooids

The influence of image dimensionality and resolution was tested for CT-generated volumetric images of a resin-impregnated ooid sand. Pore geometry determinations from 2D images were compared to those determined from 3D images, and pore geometry determinations and subsequent permeability predictions were compared for image resolutions differing by a factor of two. To address these assumptions a volumetric CT image of a homogeneous and isotropic ooid sand was collected at 11.5-μm (pixel size) resolution and then converted to a second image with 23.0-μm resolution and from these volumetric images two-dimensional images (*xy*-plane CT "slices") were "lifted". From these four sets of images pore geometry (pore body and pore throat sizes) and topology (coordination numbers—number of throats connecting nodes) were quantified and permeability was predicted using Effective Medium Theory. The findings were that 1) the mean values of the 2D and 3D pore size distributions were comparable, but the 2D pore size distribution was broader (Table 1); 2) coordination numbers averaged 3.0 for the low- and high-resolution 2D images, 4.3 for low-resolution 3D images, and 3.9 for high-resolution 3D images, indicating that 2D and 3D connectivity may be more similar than typically assumed; and 3) EMT permeability predictions are strongly influenced by image resolution. That is, high-resolution 2D and 3D images yielded permeability predictions that are a factor of two higher than measured values, whereas low-resolution 2D and 3D images yielded permeability predictions that are more than an order of magnitude higher than measured values. Ideally, image voxel size may need to be on the order of one-third the mean pore size to provide reliable permeability predictions.

Table 1. Pore body and pore throat sizes and distributions for the high- (HR) and low- (LR) resolution 3D and 2D images (units for the pore sizes are in μm)

Sample	mean	(± σ)	median	mode	number
Pore Body Radius					
HR3D	45.8	20.8	46	46	10911
HR2D	56.4	25.6	57.5	46	88642
LR3D	68.7	19.5	69	69	4977
LR2D	56.7	25.4	46	46	29208
Pore Throat Radius					
HR3D	29.3	15.0	34.5	34.5	24013
HR2D	38.0	23.5	23	23	167520
LR3D	45.1	13.8	46	46	13089
LR2D	51.8	20.2	46	46	49452
Pore Throat Length					
HR3D	323.7	257.8	115.6	282.3	24013
HR2D	168.9	122.3	141.5	31.5	167520
LR3D	321.7	140.6	299.0	277.8	13089
LR2D	201.1	155.5	167.4	32.4	49452

IMPACT/APPLICATIONS

Understanding and modeling the phenomena of penetration of high-frequency sound at low grazing angles into the sea floor will aid in mine detection and classification for the navy.

TRANSITIONS

The results of this basic research are used in developing acoustic models for seafloor scattering. The database is potentially useful for inclusion in the NAVOCEANO shallow-water MIW sediment database.

RELATED PROJECTS

ONR's Mine Burial Processes (MBP) 6.2 program is indirectly related to this 6.1 research. Predicting burial state of mines on the sea floor is another facet of information, along with the acoustic predictions for scattering strength of seafloor targets, in the decision process in mine hunting.

Ray Lim at Coastal Systems Station, Panama City Beach, FL is involved in developing techniques for modeling acoustic scattering from buried objects, especially including the effects of sediment interface roughness in coupling acoustic energy into the sediment at subcritical grazing angles. Our characterization of the rough interface at SAX99 has a direct bearing on CSS modeling efforts.

ONR is funding Peter Jumars (UMe) and Chris Jones (APL-UW) in a high-frequency acoustic project to study the effects of benthic biological processes on backscattering. An important component of this research involves photogrammetric determination of temporal roughness variability.

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HONORS/AWARDS/PRIZES

Naval Research Laboratory's 2003 Berman Award for outstanding paper from NRL's Seafloor Sciences Branch: Richardson, M.D., K.L. Williams, K.B. Briggs and E.I. Thorsos. 2002. Dynamic measurement of sediment grain compressibility at atmospheric pressure: acoustic implications. *IEEE Journal of Oceanic Engineering,* 27(3): 593-601.